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POSSIBLE NEUTRALITY OF COSMIC RADIATION

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In this note, we wish to point out that recent observations from satellites indicate a similarity between the low-energy, relativistic cosmic-ray electron and proton differential velocity spectra. This suggests a new point of view: that the total numbers of electrons and of charged nucleons in cosmic radiation are equal. The implications of this equality and of the low-energy spectral forms are discussed. In particular, the Fermi-like acceleration of protons and of electrons from distributed rather than from discrete sources is implied.

During the last several decades it has become generally accepted that cosmic radiation consists of positively charged particles, mostly protons, with a fraction of alphas and other nuclei. Measurements of cosmic rays with energies above several BeV indicated that an upper limit to the electron-photon component is below one percent of this primary radiation [1,2]. Further, the observation of radio emission from the galaxy implied that high-energy electrons should indeed be present there, but with a small fraction of the galactic proton intensity. Electrons with medium energies, in the BeV region, were subsequently found at

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balloon altitudes[3,4] with an integral intensity only a few percent that of all cosmic rays. More recently, electrons with orders of magnitude lower energy, in the few-MeV region, were found in interplanetary space[5]. We assume, as a working hypothesis, that the electrons of these extremely low energies are also cosmic rays; as discussed by the observers, all of the properties of this component are consistent with galactic origin, and none are inconsistent with it. The integral intensity of these electrons is below 10 percent of the total observed cosmic-ray intensity, but the spectrum rises towards the lower energies, implying that a greater number may be present there. Rather than describing the electron and nucleon observations in terms of energy or of rigidity, as is usually the custom, we choose a parameter based on velocity alone, the total energy per unit mass, $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$. We believe this to be the appropriate unit at the low cosmic-ray energies for considering acceleration and propagation; Fermi's model of cosmic ray acceleration[6] depends only on γ, and Parker's model of modulation at asymptotically low particle rigidity[7] depends only on β, independent of other parameters such as mass or charge. It is possible that combinations or variations of these models describe a great share of low-energy cosmic-ray behavior. The differential intensities $dJ/d\gamma$ of the electrons, protons, and alphas of lowest observed energies[5,8,9,10,11] are shown in Figure 1a. Throughout the region $\gamma < 2$, the proton and alpha observations fit a common curve when the alpha intensities are multiplied by an abundance correction of about 5. An analytic expression[12] which fits these 1963 proton and alpha data throughout the low-energy region is plotted as a dashed curve in order to provide a comparison with the electrons. We note that the electrons in the $6 < \gamma < 25$ region, within the measurement errors, have nearly the same spectral distribution as the protons. Unlike the case of the alphas, no relative abundance correction is needed; the two spectra have the same slope and the same coefficient. If it is found, as the data suggest, that the electron intensity continues to increase with the same slope towards the non-relativistic region where most of the protons are found, it will result that the total numbers of electrons and of protons are essentially equal. Since protons carry the bulk of the positive charge in cosmic rays, it is within the measurement errors to further speculate that cosmic radiation is neutral. Thus, the historical point of view that the cosmic-ray electron/proton ratio is small arose from observing and discussing data with a detection bias based on energy, rather than on velocity.

This assertion of spectral equality must be qualified because of the uncertainty of our knowledge of interplanetary modulation. All of the electron and nucleon measurements quoted were made at about the same time, so that the corrections needed to obtain the galactic spectra are at least compatible; since that time was only a year or two before solar minimum, the corrections are less severe than otherwise would be the case. We assume as correct the modulation model[7] in which the protons with $\gamma < 2$ and the electrons with $\gamma \ll 10^3$ have velocity-dependent intensity corrections given by $\exp(K/\beta)$. Here, K is not accurately known, but is believed to be near unity, while $(\Delta K/K\Delta t)$ is more accurately known to be about 0.1 per year[13]. The 1963 nucleon data are replotted in Figure 1b with this correction incorporated for several values of K. An intermediate proton measurement[14], asympotic to the region where the modulation is rigidity dependent, and also a fit to the high-energy cosmic-ray spectrum[15], where the modulation is presumably negligible, are shown for comparison. It is seen that the proton data demodulated with K=1.0 fit a power law in total energy all the way through $1.02 < \gamma < 100$; $dJ/d\gamma = (1.15 \pm 0.15) \times \gamma^{-2.5 \pm 0.1}$ particles/cm^2sec sr unit γ. The electron data are replotted with the K=1.0 demodulation factor of 2.7 incorporated; they fit the proton spectrum to within the experimental uncertainties and, we note, this fit is only weakly dependent on the choice of K. (Electron measurements in the $10^2 < \gamma < 10^5$ region are not shown; the observed spectrum is less steep there, such that at $\gamma = 10^4$ it exceeds the proton intensity by between one and two orders of magnitude. This spectral separation may be due to high-energy effects such as rigidity-dependent acceleration and modulation, and to energy-dependent secondary meson production; we believe that it does not directly affect arguments as to the injection and acceleration mechanisms in the very low-γ region.) If we accept the conclusion that outside the solar system the proton and electron spectra in the low-γ region are essentially the same, and if we choose not to interpret this as a meaningless accident, then we are led to believe that this observed fact may be of importance in understanding the origin of cosmic-ray particles.

We may conjecture, for example, that these electrons and protons have a common origin. The shape of the demodulated spectrum in Figure 1b is suggestive of the Fermi acceleration, being a power law in total energy per unit mass. The interesting difference between this and other treatments[8,12] is that these data fit the Fermi spectrum after the correction for solar modulation is applied but <u>before</u> the usual correction for 2.5 g cm^{-2} galactic path length is applied. Ionization losses for such low-energy particles are severe, yet the observations (a) that the electrons are not stopped due to ionization losses (in spite of their exceedingly low energies), (b) that these protons fit a power law in γ down to the non-relativistic region (as though ionization losses did not occur, or were more than counteracted by acceleration), and (c), that the electrons and protons fit the same spectrum in γ, are all results of the Fermi model[6] when ionized material with bulk neutrality is injected. It is clear that, if we consider discrete sources such as supernovae or a galactic-center catastrophe, the source spectra of electrons and of protons would not be maintained after interstellar particle propagation through 2.5 g cm^{-2} to the point of observation. Given that the observed electron and proton spectra are the same, the electron intensity at the discrete source, because of the ionization loss, must have been much greater than the proton intensity there. (For example, an electron observed to have a γ of 5.5 would have $\gamma \approx 30$ at its origin, whereas an observed proton with that γ would have started with essentially the same value. The electron/proton intensity ratio at the source for these values of γ would be greater than 30, given the ratio of unity at the solar system, and it would become progressively larger towards lower energies.) For the electrons and protons to have started with a velocity-dependent intensity ratio such that their traversal through the galactic material accidentally gives rise to the observed velocity-independent ratio of unity seems an unlikely coincidence. An alternative and aesthetically preferable possibility is that these low-energy electrons are produced in a distributed manner such that the ionization losses are overcome by continuous injection and acceleration. The Fermi model of acceleration by collisions of cosmic rays of mean life τ with scattering centers of velocity $V = Bc$ yields a time rate of normalized energy increase $d\gamma/dt = B^2\gamma/\tau \equiv \alpha\gamma$. For this energy increase to exceed the ionization loss even at low particle β, we have $\alpha\gamma > \rho\beta c\,|d\gamma/dX|$, in which ρ is the matter density in g cm^{-3} and $|d\gamma/dX|$ is the normalized energy loss / g cm^{-2}. This inequality is solved for the injection value of γ by use of the curves shown in Figure 2. We note that α must be in the neighborhood of 10^{-14}/sec for the injection γ of electrons to be non-relativistic, assuming a galactic value of $\rho = 2 \times 10^{-26}$ g cm^{-3}. This value is of the same order or slightly higher than that α found[16] to be required to boost the secondary galactic knock-on electrons to fit the observations. The trouble with this view of the Fermi mechanism operating down to sub-relativistic energies is that observations of medium nuclei[12, 17] indicate that the intensities of such particles, after solar demodulation, fit the same velocity spectrum as the alphas only after 1 to 2 grams of interstellar material is taken into account. The recent measurements of very heavy nuclei[18, 19], however fit the same source spectrum after the passage through very little material is incorporated. These data are more in agreement with this interpretation, although the overall picture is definitely controversial. Finally, if a metagalactic origin of cosmic rays is considered, then it may be that electrons and protons find their way to the solar system after passage through very little galactic matter, such that a power-law source spectrum with spectral neutrality is preserved down to low energies. In this case, since $\rho_{mg}/\rho_g \approx 10^{-3}$ and since the energy loss per g cm^{-2} outside the galaxy is about twice that inside, the value of α_{mg} would be about 10^{-17}/sec.

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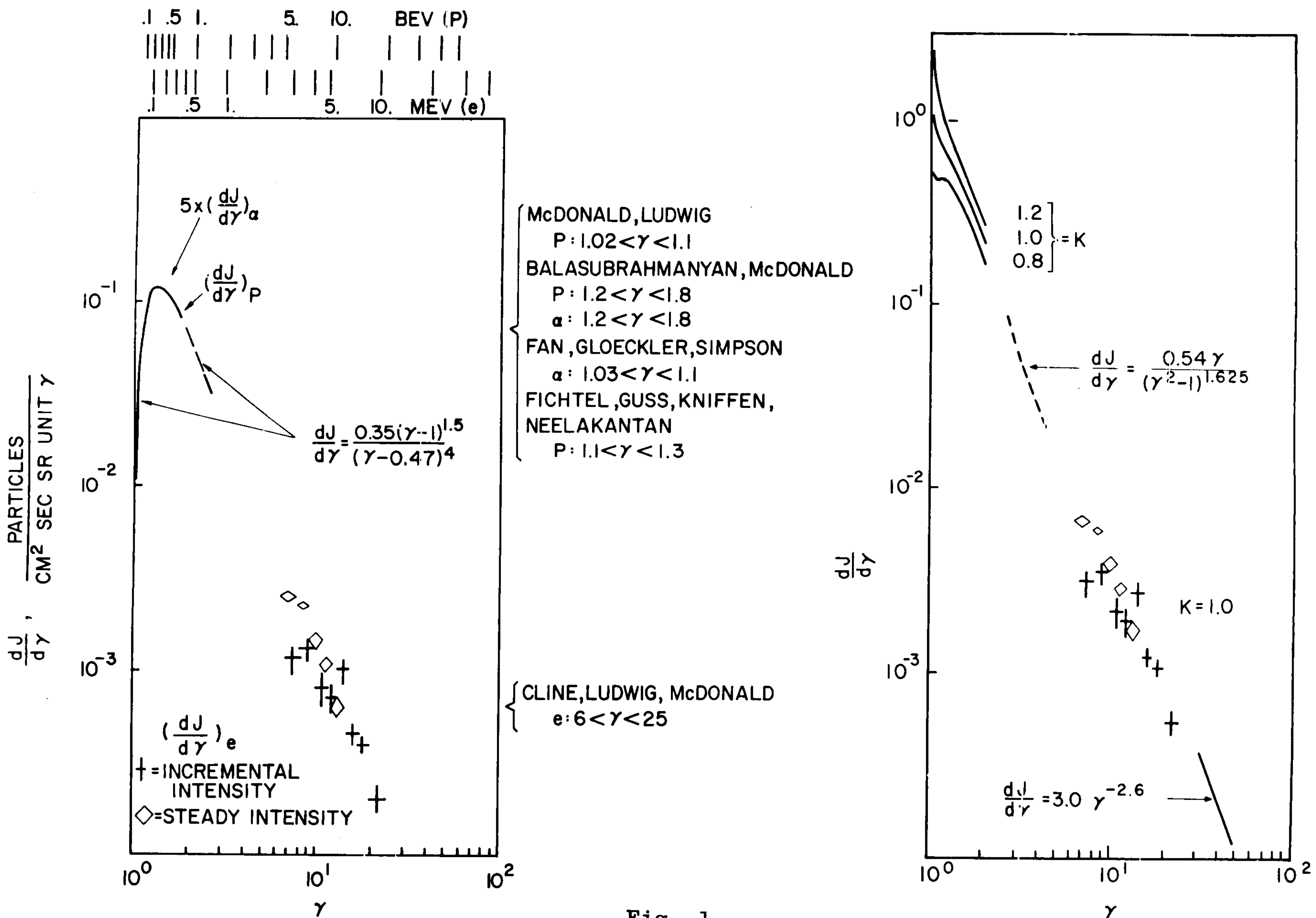
Fig. 1. a) The observed differential energy per unit mass spectra of low-energy cosmic-ray electrons, protons and alphas. The solid curve is a smooth fit to a composite of the proton and alpha measurements[8,9,10,11] and the dashed curve is its extrapolation[12]. The other measurements are those of low-energy interplanetary electrons[5]. The maximum electron intensity observed is the sum of the two spectra shown.

b) The same proton data altered by use of the factor $\exp(K/\beta)$ with three values of K and the electron data altered with K = 1. Intermediate and high-energy proton spectra derived from integral distributions[14,15] are shown for comparison. A fit to all these data is $dJ/d\gamma = (1.15 \pm .15)\ \gamma^{-2.5 \pm .1}$ particles/cm^{2}sec sr unit γ.

Fig. 2. The equation $\gamma' = \rho\beta c\ |d\gamma/dX|\ /\alpha$ plotted for several values of the parameter α. The normalized energy at which a curve for γ' crosses the curve for γ is the injection energy; electrons with at least that γ experience greater energy gain from Fermi acceleration than energy loss from ionization.



.1 .5 1. 5. 10. BEV (P)
.1 .5 1. 5. 10. MEV (e)
$\frac{dJ}{d\gamma}$, $\frac{\text{PARTICLES}}{\text{CM}^2 \text{ SEC SR UNIT } \gamma}$
$5\times(\frac{dJ}{d\gamma})_\alpha$
$(\frac{dJ}{d\gamma})_P$
$\frac{dJ}{d\gamma} = \frac{0.35(\gamma-1)^{1.5}}{(\gamma-0.47)^4}$
$(\frac{dJ}{d\gamma})_e$
+ = INCREMENTAL INTENSITY
◇ = STEADY INTENSITY
McDONALD, LUDWIG
P: $1.02<\gamma<1.1$
BALASUBRAHMANYAN, McDONALD
P: $1.2<\gamma<1.8$
α: $1.2<\gamma<1.8$
FAN, GLOECKLER, SIMPSON
α: $1.03<\gamma<1.1$
FICHTEL, GUSS, KNIFFEN, NEELAKANTAN
P: $1.1<\gamma<1.3$
CLINE, LUDWIG, McDONALD
e: $6<\gamma<25$
γ
$\frac{dJ}{d\gamma}$
1.2
1.0
0.8
= K
$\frac{dJ}{d\gamma} = \frac{0.54\gamma}{(\gamma^2-1)^{1.625}}$
K = 1.0
$\frac{dJ}{d\gamma} = 3.0\ \gamma^{-2.6}$

Fig. 1.

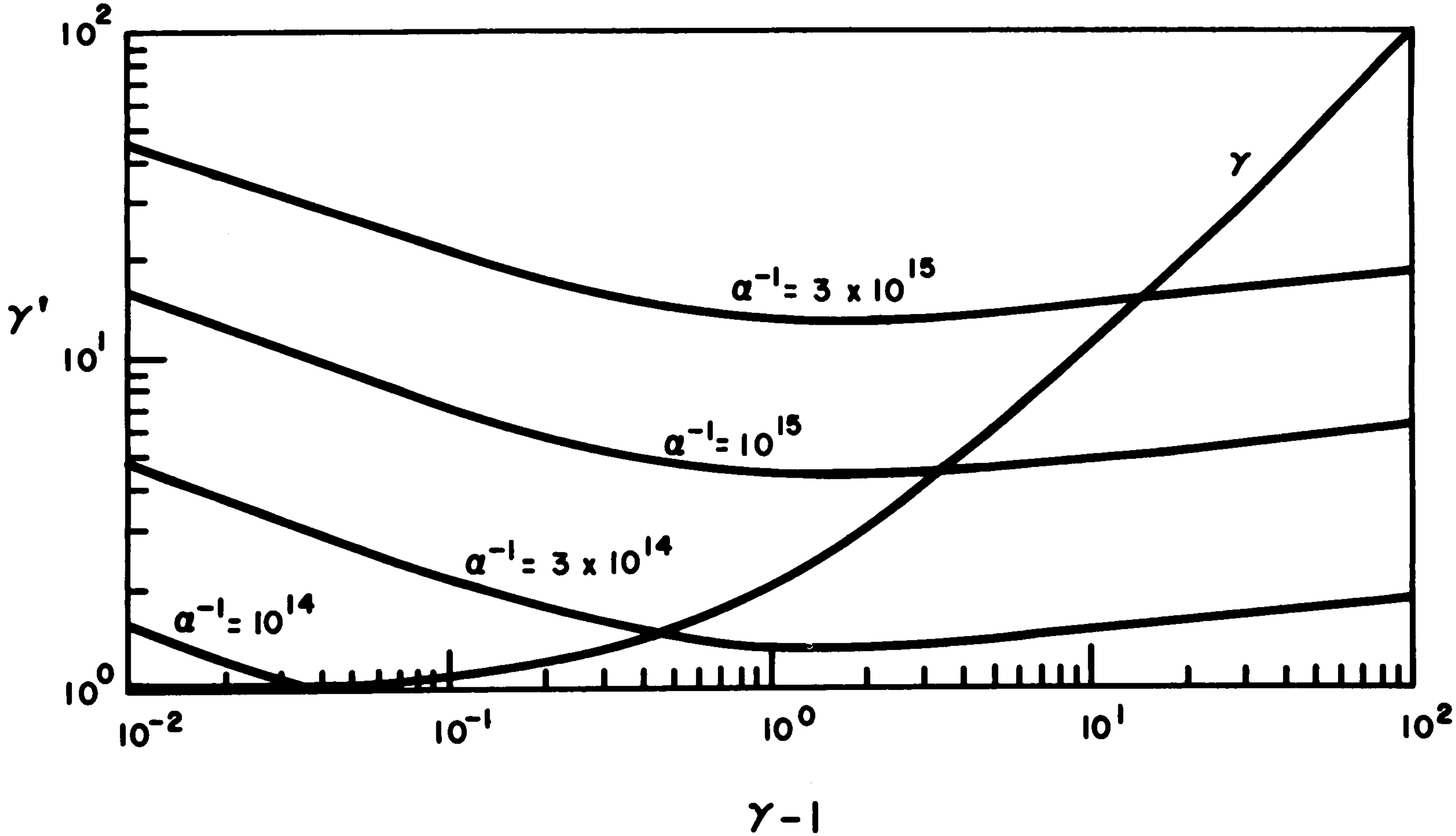

10^2
γ'
10^1
10^0
γ
$\alpha^{-1} = 3 \times 10^{15}$
$\alpha^{-1} = 10^{15}$
$\alpha^{-1} = 3 \times 10^{14}$
$\alpha^{-1} = 10^{14}$
10^{-2}
10^{-1}
10^0
10^1
10^2
$\gamma - 1$

Fig. 2.